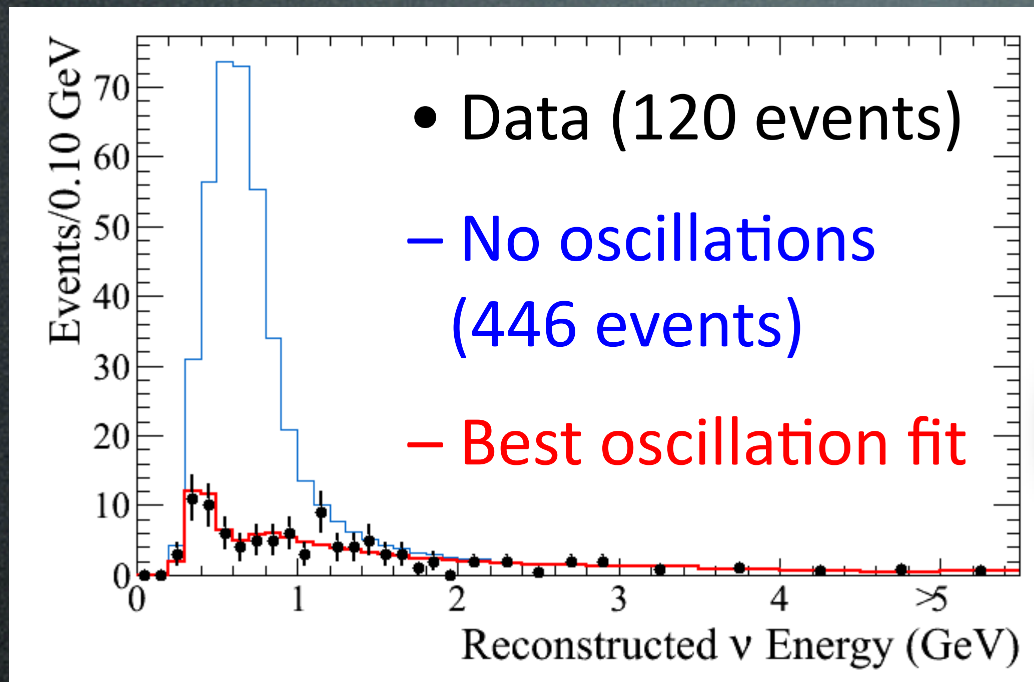
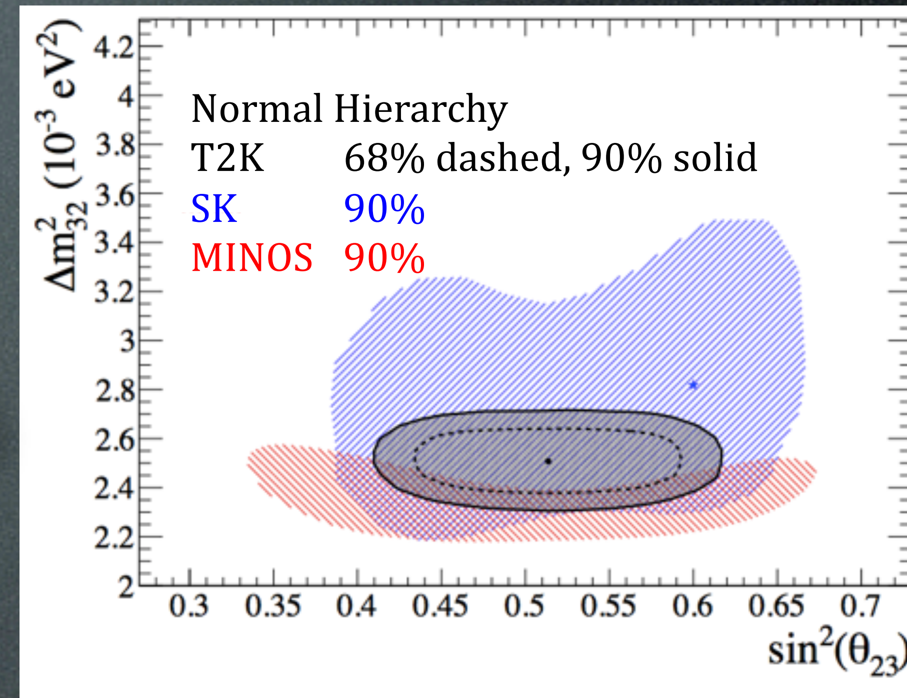
T2K Sensitivities to Neutrino Oscillation Parameters

Mike Wilking, Stony Brook University
Workshop on the Intermediate Neutrino Program
5-Feb-2015

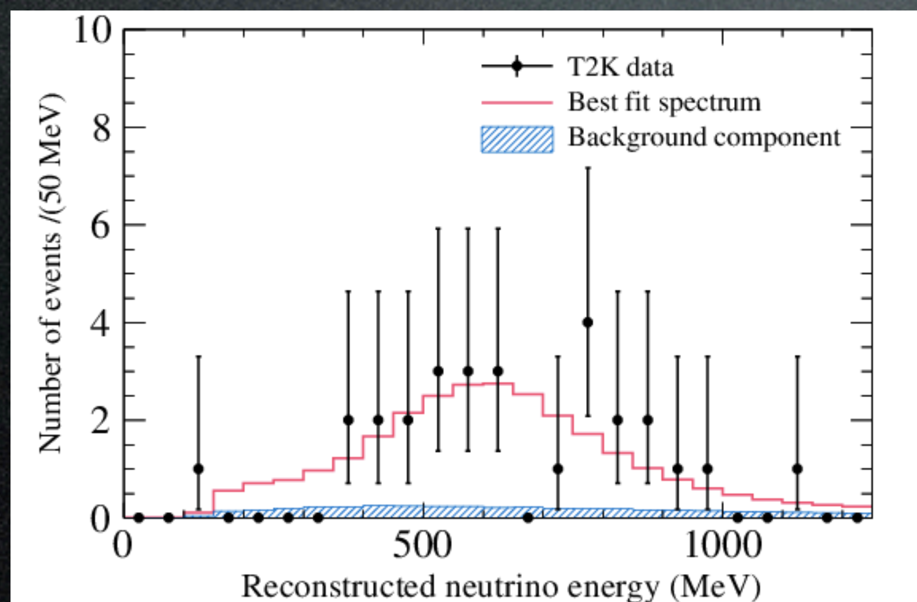
Where are we now?

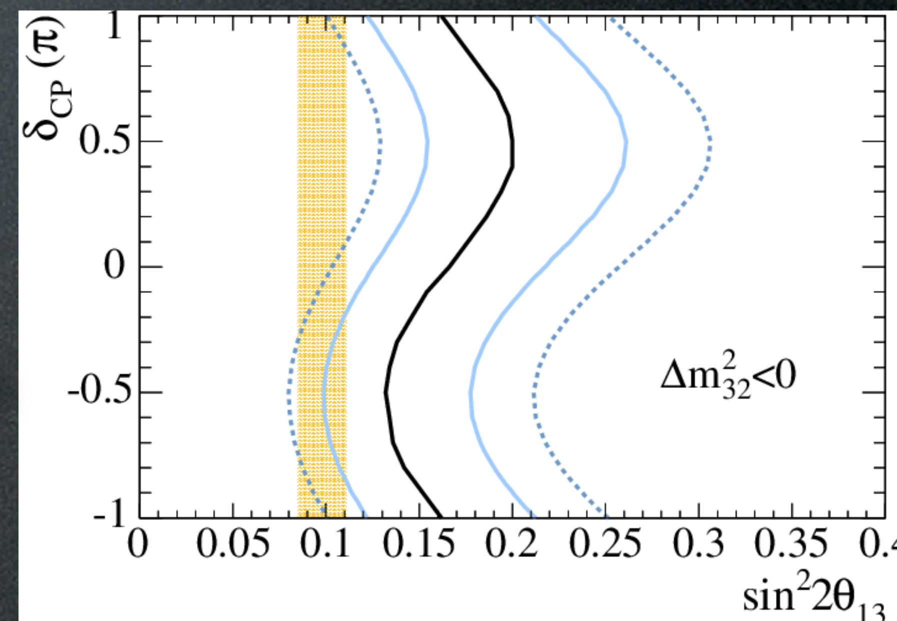
ν_μ disappearance





ν_e disappearance

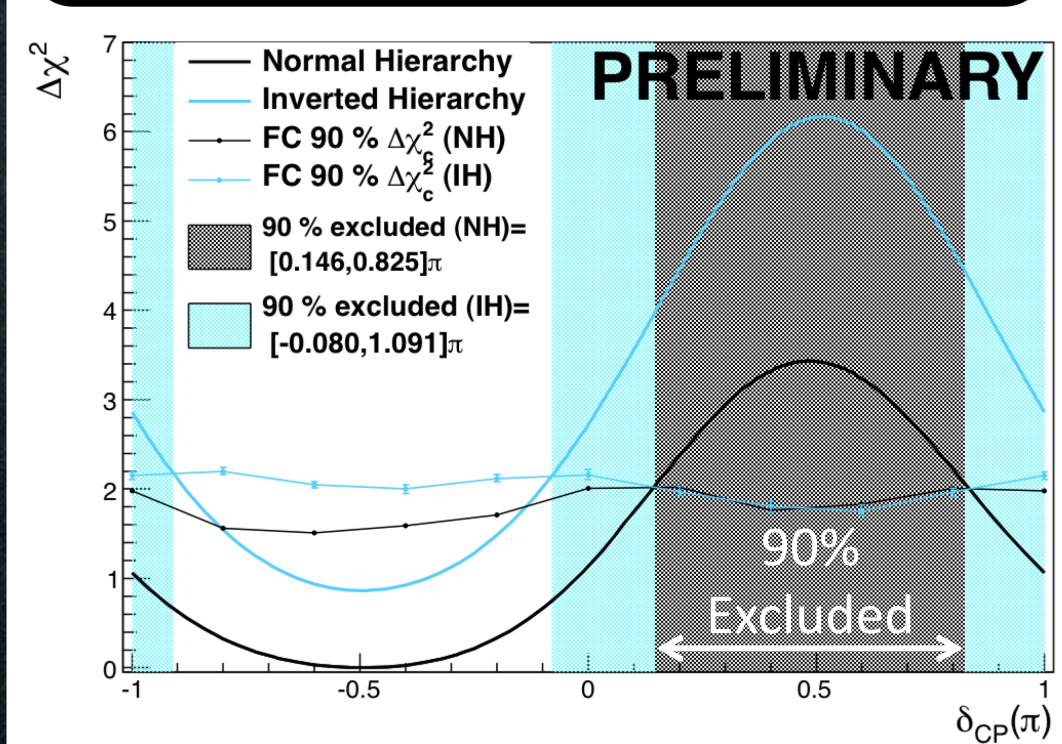




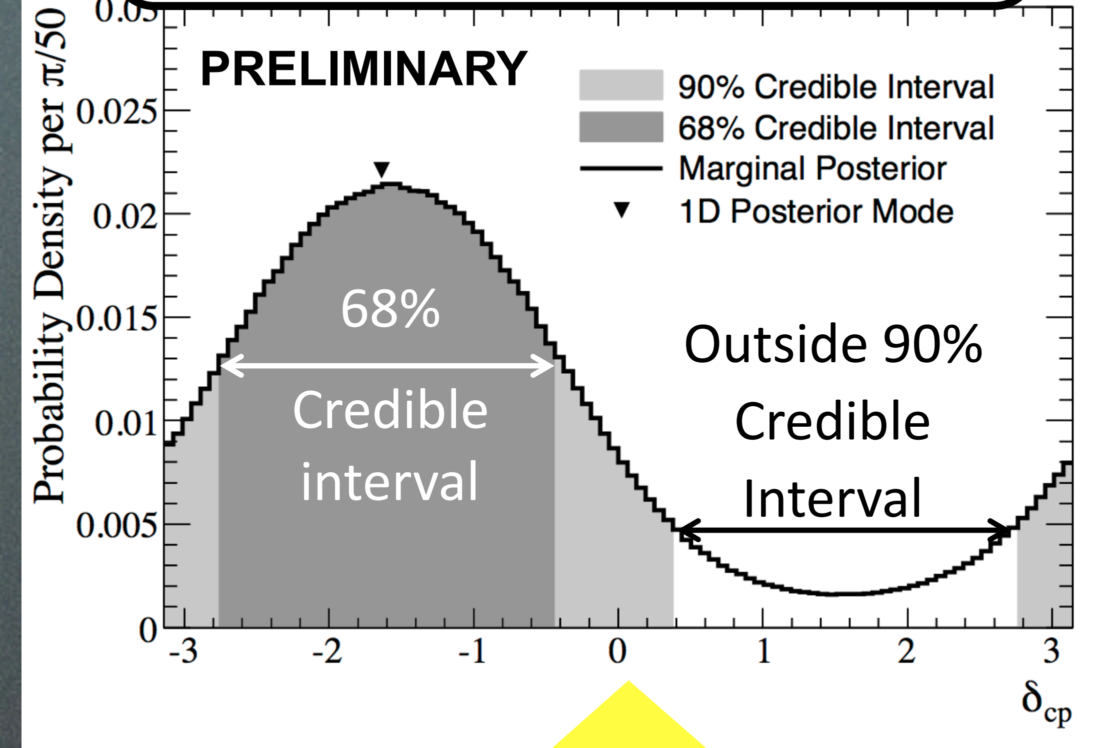
- Most precise measurement of θ_{23}
- First observation of ν_e appearance (7.3σ)

CP Violation

Frequentist Exclusion Limit



Bayesian Credible Interval



- $\nu_e+\nu_\mu$ fit with reactor constraint
  - $\sin^2 2\theta_{13}=0.095\pm0.010$ (PDG 2013)
- Both Frequentist (left) and Bayesian (right) methods
- Best fit at $\delta_{CP}=-\pi/2$
- Slight preference for $\theta_{23}>\pi/2$ and normal hierarchy

	NH	IH	Sum
$\sin^2\theta_{23}\leq0.5$	0.179	0.078	0.257
$\sin^2\theta_{23}>0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.00

posterior probabilities marginalizing over other parameters

What precision can T2K ultimately reach?

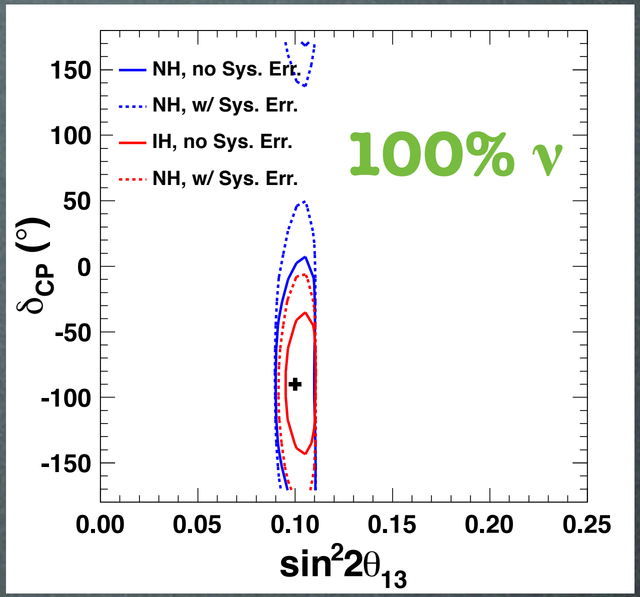
http://arxiv.org/abs/1409.7469

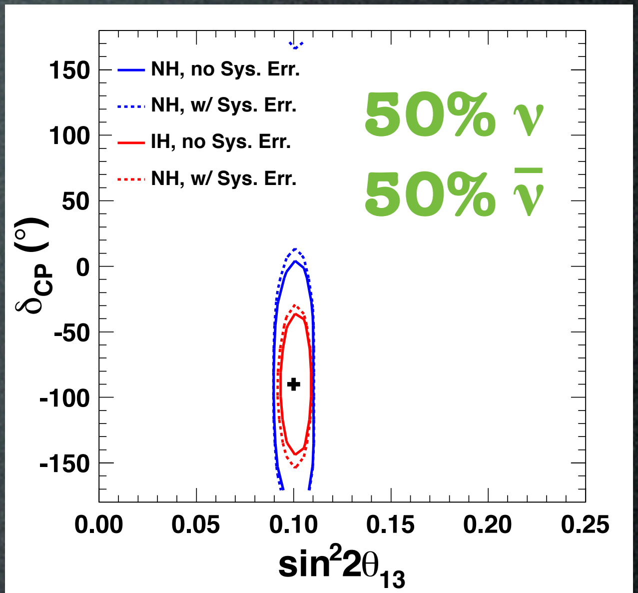
T2K Run Plan

Sensitivities with full 7.8 x 10^{21} POT

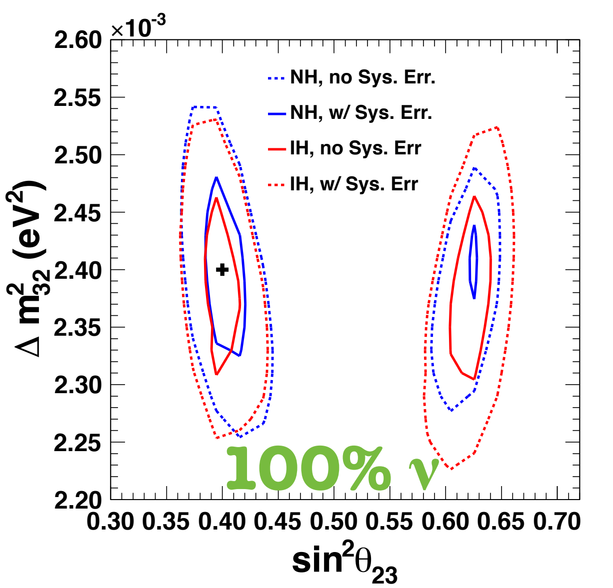
Assumed ultimate reactor constraint of $\sin^2 2\theta_{13}=0.01\pm0.005$

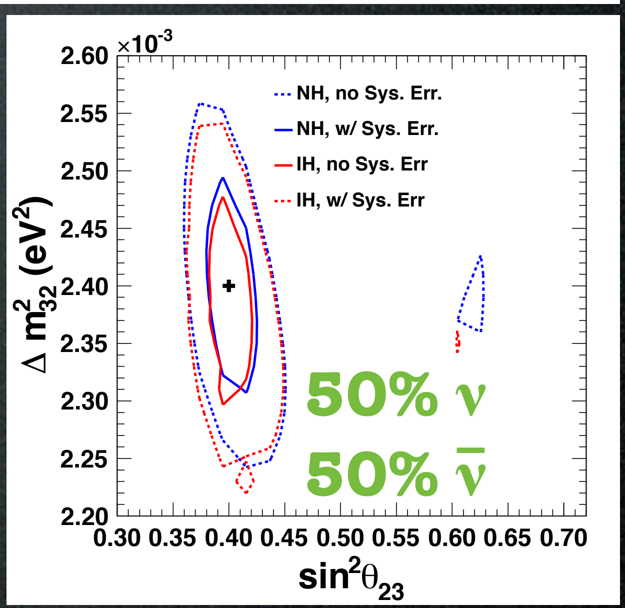
δ_{CP}





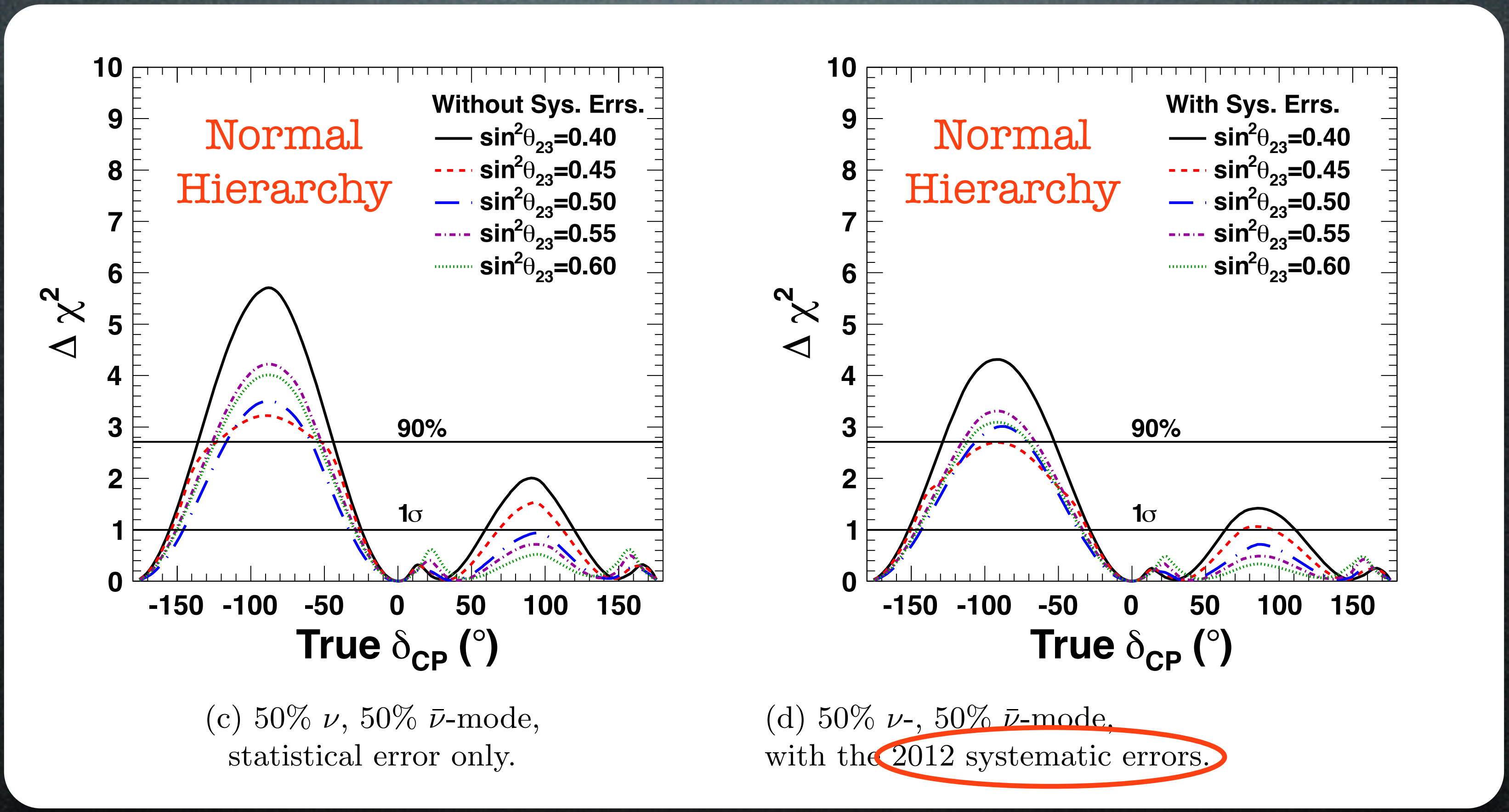
θ_{23} Octant





- Running with both neutrinos and anti-neutrinos improves T2K sensitivity to both δ_{CP} and the θ_{23} octant
  - Cancelation of systematic errors between ν and $\bar{\nu}$
  - Breaks degeneracy between effects of δ_{CP} and θ_{23}

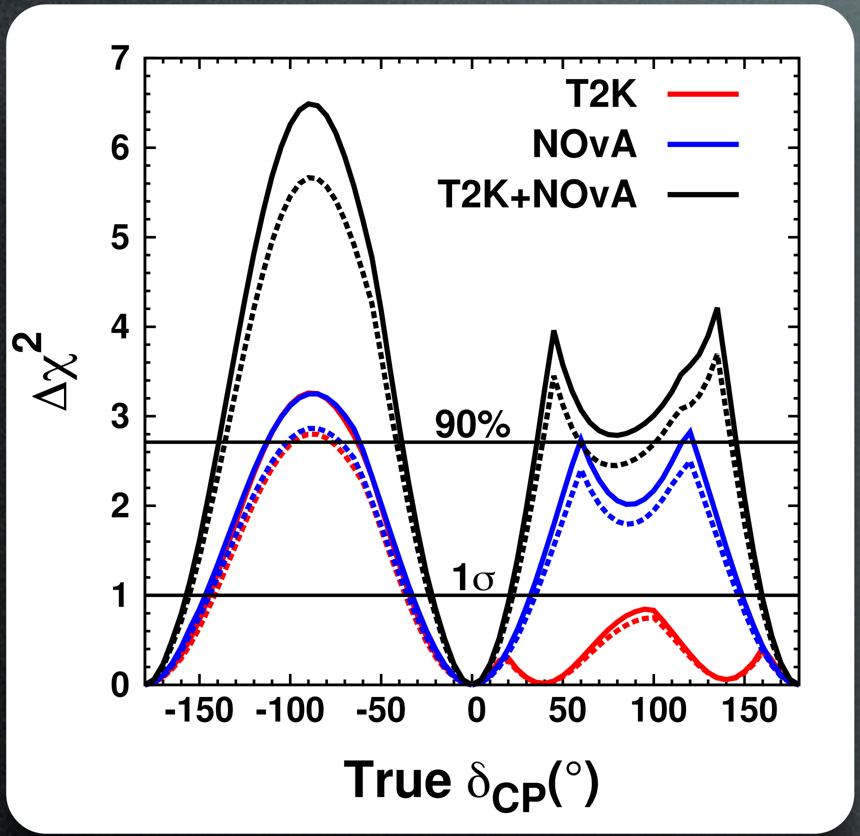
T2K CP Violation Sensitivity



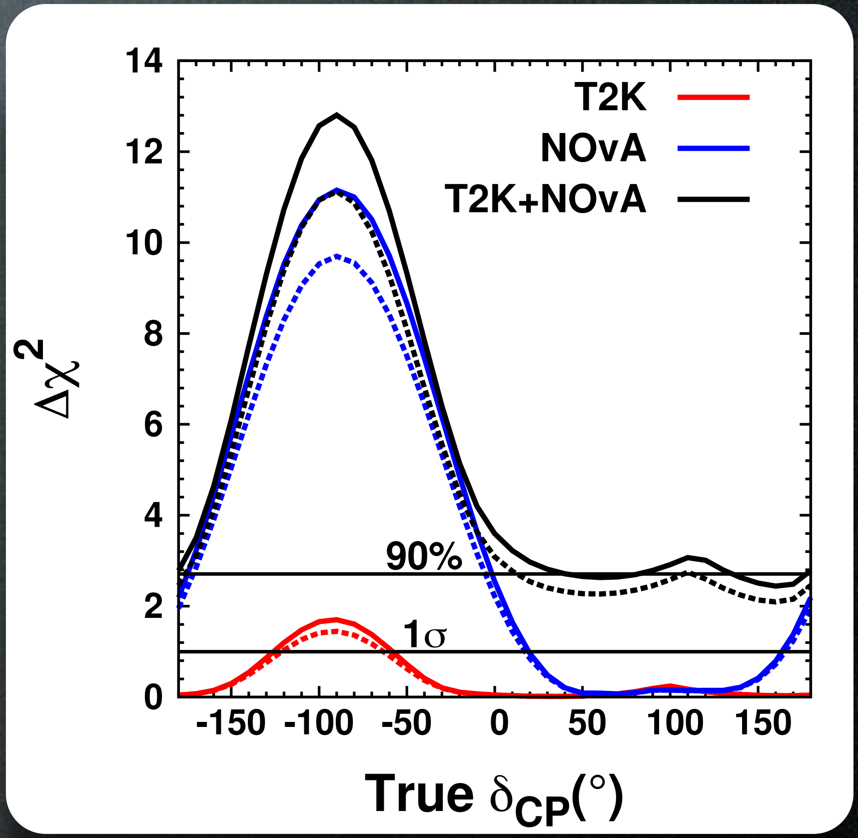
- CP violation sensitivity depends on the MH and θ_{23}
  - For the most fortunate choice of parameters, T2K is sensitive to CP violation at the 2-2.5 σ level
- At final approved POT (7.8×10^{21}), systematic errors become important

T2K + NOνA

δ_{CP}:



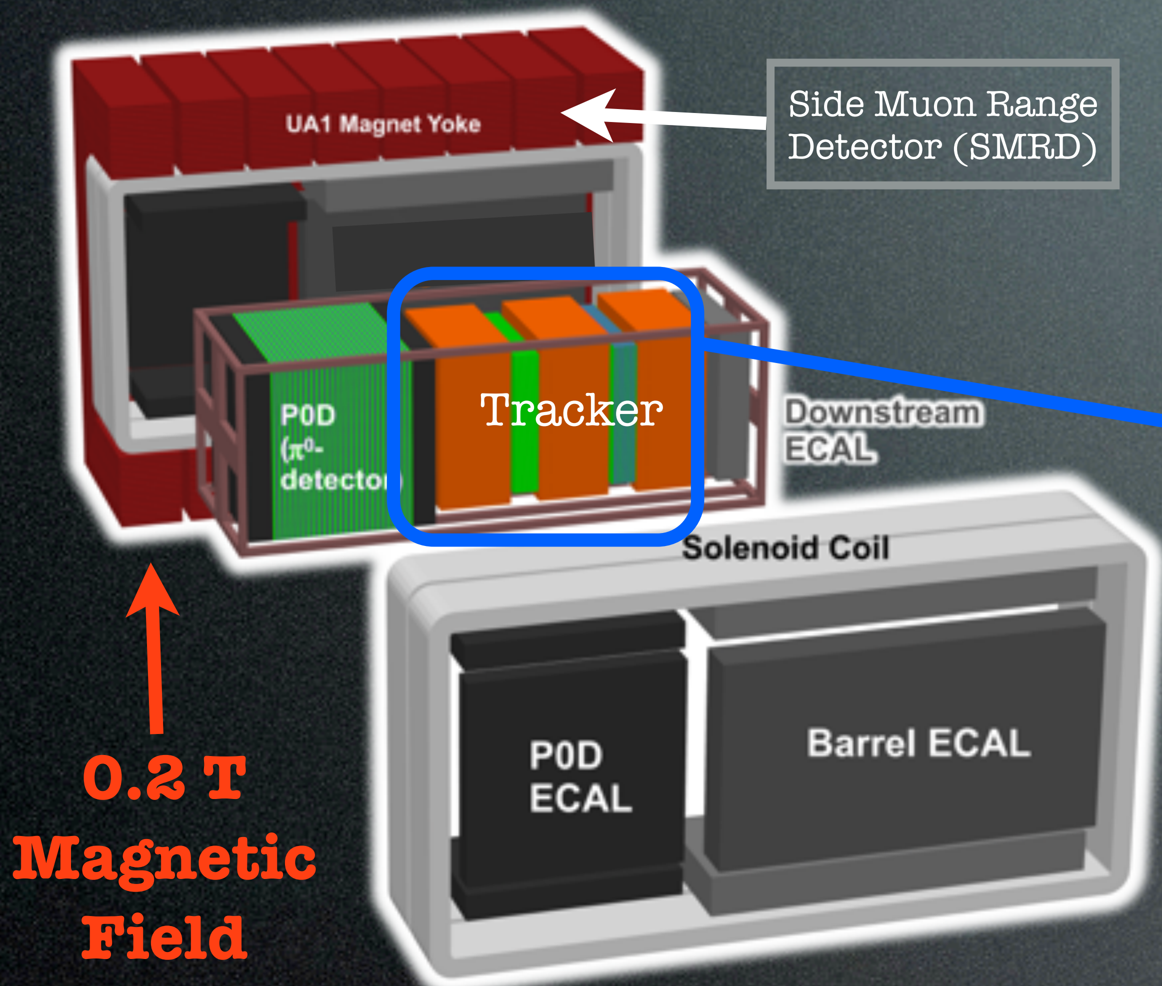
MH:

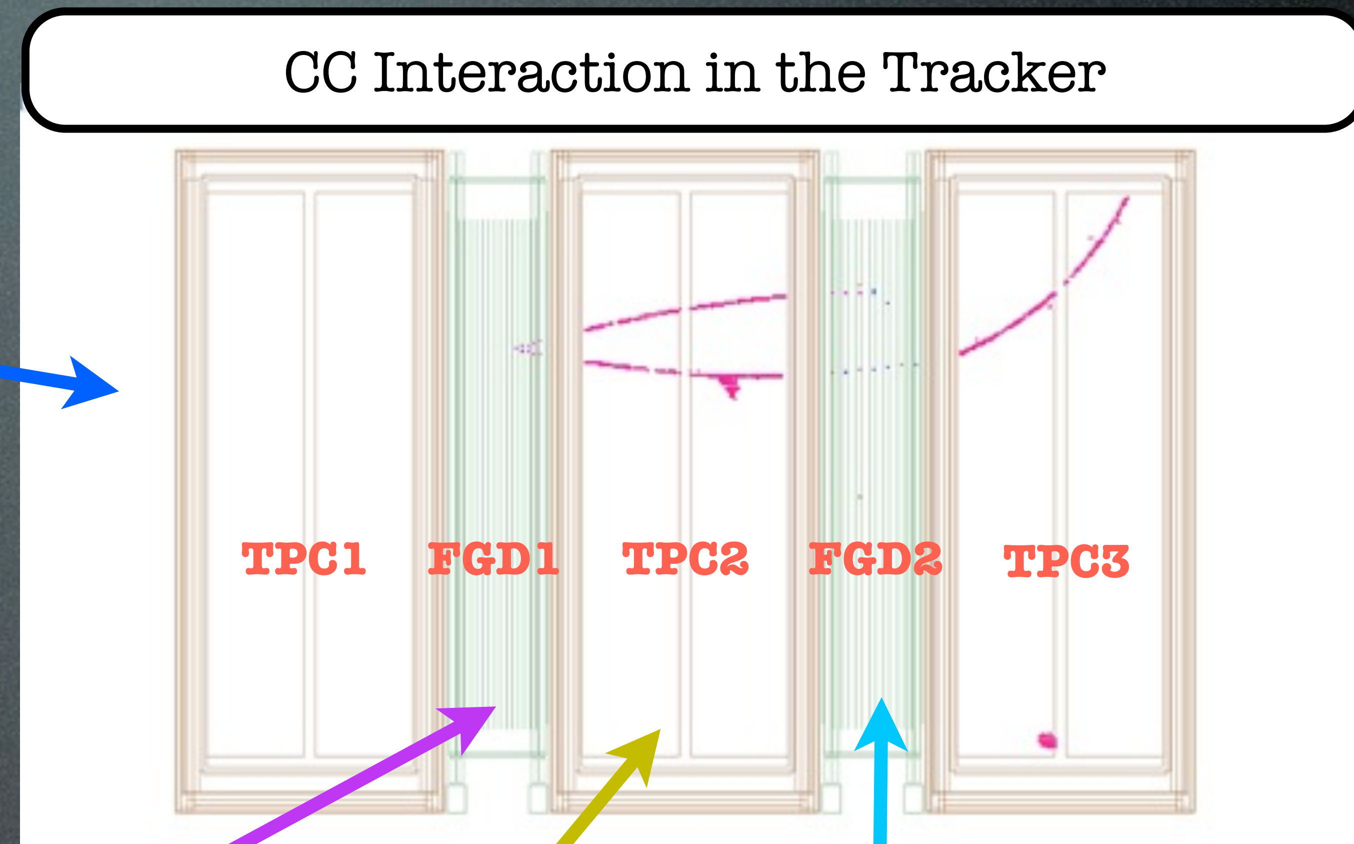


- T2K and NOνA have similar sensitivity to CP violation
- NOνA's sensitivity to the mass hierarchy is enhanced by combining with T2K data
- All results shown so far are available here: http://arxiv.org/abs/1409.7469

T2K Systematic Error Projections

T2K Near Detector Constraints





FGD2 has water layers to constrain interactions on same target as Super-K

Not yet used; planned 2015 analysis improvement

Fine-Grained Detectors (FGDs)

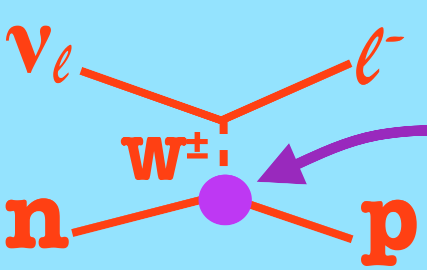
- Scintillator strips
- Provides neutrino target
- Detailed vertex information

Time Projection Chambers (TPCs)

- Gas ionization chambers
- Track momentum from curvature
- Particle ID from dE/dx

2012 Cross Section Model

CCQE



Main difficulty is in understanding the hadronic current

However, the vector form factors are known from electron scattering!

- Remaining axial vector form factor has 2 parameters
- $F_A(0)$ is known from beta decay experiments
- M_A is the only free parameter

$$F_A(Q^2) = \frac{F_A(0)}{(1+\frac{Q^2}{M_A^2})^2}$$

CCπ^+

- More complicated (and ad hoc)
- Has its own M_A parameter
- Pion-less Δ decay added by hand

Nuclear Model

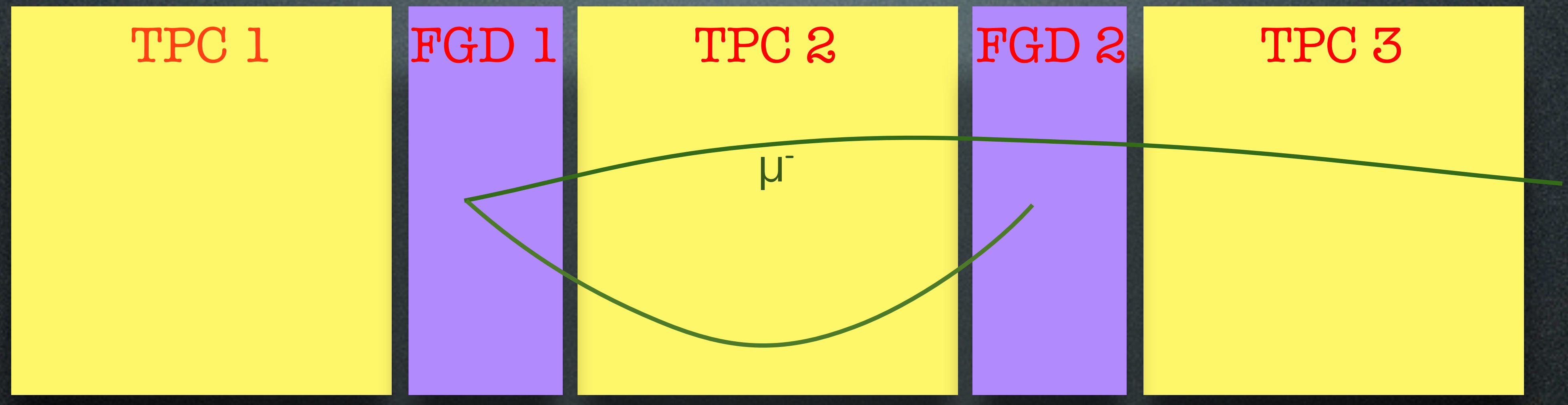
- Relativistic Fermi Gas (binding energy + p_{Fermi})
- Can also reweight to a spectral function treatment

Other

- Norm. factors are varied for other processes

Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	norm
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	norm
CCQE E3	$E_\nu > 3.5$	1.0	0.30	norm
CC1π E1	$0 < E_\nu < 2.5$	1.15	0.43	norm
CC1π E2	$E_\nu > 2.5$	1.0	0.40	norm
CC Coh	all	1.0	1.0	norm
NC1π^0	all	0.96	0.43	norm
NC 1$\pi^\pm$	all	1.0	0.3	norm
NC Coh	all	1.0	0.3	norm
NC other	all	1.0	0.30	norm
ν_μ/ν_e	all	1.0	0.03	norm
$\nu/\bar{\nu}$	all	1.0	0.40	norm

2012 Event Selection



- Charged-Current events were separated into 2 categories:
  - **CCQE-like sample** (1-track events)
    - 70% CCQE purity (95% at osc. max)
    - **CCQE parameters are well constrained**
  - **CCnonQE-like sample** (>1-track events)
    - 29% CCπ^+ purity
    - **CCπ^+ parameters are poorly constrained**

Limitations of the 2012 Near Detector Analysis

- Doubling the data statistics produced only a small reduction in the error on the far detector event rate
- The diagonal error on the cross section parameters were unchanged
  - (some small improvement in the correlated error)

Error on T2K ν_e Candidate Prediction (After Near Detector Constraint)

$\sin^2 2\theta_{13}$	Using Data from Runs 1-2	Using Data from Runs 1-3
0.1	5.7%	4.7%
0.0	6.7%	6.1%

Statistics doubled

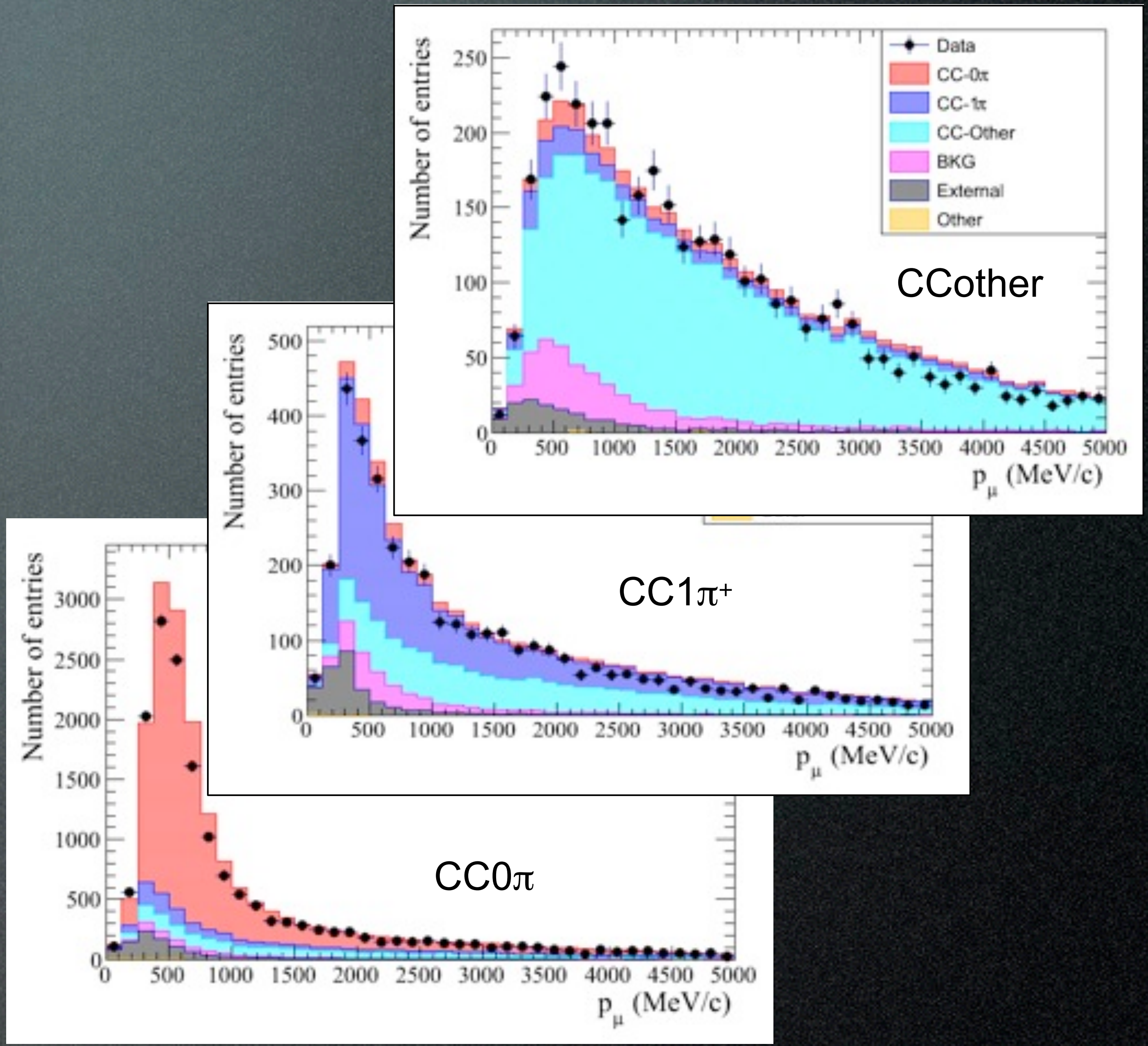
Error on Cross Section Parameters (After Near Detector Constraint)

Parameter	Run 1-2 Data	Runs 1-3 Data
M_A^{QE} (GeV/c^2)	1.17 ± 0.19	1.27 ± 0.19
M_A^{RES} (GeV/c^2)	1.25 ± 0.14	1.22 ± 0.13
CCQE Norm.	0.95 ± 0.09	0.95 ± 0.09
CC1π Norm.	1.33 ± 0.22	1.37 ± 0.20

Statistics doubled

2013 Analysis

- Separate the CC sample into three subsamples:
  - CC0π: **no pions** in the final state
  - CC1π+: exactly **1 π+** in the final state
  - CCother: **>1 π+** OR **>0 π-** OR **>0 tagged photons**
- Higher purities for all 3 samples, relative to the 2012 analysis
  - Much better samples for constraining CCQE and CCπ+ cross section parameters



	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-ν)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

Summary of Improvements

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

*Results presented at Neutrino 2012 conference

**Published results, arXiv:1304.0841v2

***Update to NEUT tuning with MiniBooNE data

2012 Analysis was systematics limited

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

2013 Analysis method gave a big improvement

The parameters that can be constrained are now very well constrained!

Systematics Reduction

- Largest remaining uncertainties in both ν_e appearance and ν_μ disappearance are unconstrained cross sections
  - Currently, these errors are dominated by nuclear model uncertainties
  - Expect these errors to be reduced when ND280 water measurement is included
- Is ~3% systematic error achievable?

T2K ν_e Appearance PRL

TABLE II. The uncertainty (RMS/mean in %) on the predicted number of signal ν_e events for each group of systematic uncertainties for $\sin^2 2\theta_{13} = 0.1$ and 0.

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

BANFF parameters **before** and **after** ND280 fit

non-BANFF parameters **unconstrained** by fit

T2K ν_μ Disappearance

Table 13: Uncertainty (r.m.s./mean in %) on the $N^{SK}_{\rm exp}$ distribution from each group of systematic error source. Systematic parameters refined by the ND280 fit represent "ND280 fit". Mean systematic parameter values after the ND280 fit are used for the both systematic error sets before/after the ND280 fit.

Error source	$(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4\times10^{-3})$ Before ND280 fit	After ND280 fit
BANFF-constrained Flux and ν interactions	21.6	2.7
Unconstrained ν interactions	5.9	4.9
SK detector + FSI-SI	6.3	5.6
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{12}, δ_{CP}	0.2	0.2
Total	23.4	8.1

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.6	7.2	11.4	7.4
M_A^{QE}	15.2	2.3	20.7	3.1
M_A^{RES}	7.1	2.2	3.2	1.0
CCQE norm. ($E_\nu < 1.5$ GeV)	6.9	4.7	9.0	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.6	2.4	4.0	2.0
NC1π^0 norm.	2.5	1.9	0.6	0.4
CC other shape	0.3	0.3	0.1	0.1
Spectral Function	4.7	4.7	5.9	5.9
p_F	0.1	0.1	0.1	0.1
CC coh. norm.	0.3	0.3	0.2	0.2
NC coh. norm.	1.1	1.1	0.2	0.2
NC other norm.	2.2	2.2	0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4	2.4	2.8	2.8
W shape	1.0	1.0	0.2	0.2
pion-less Δ decay	3.2	3.2	3.6	3.6
SK detector eff.	5.6	5.6	2.4	2.4
FSI	3.0	3.0	2.3	2.3
PN	3.4	3.4	0.8	0.8
SK momentum scale	1.5	1.5	0.6	0.6
Total	24.0	11.1	27.2	8.8

ND280 fit constrained

nuclear model (C vs O)

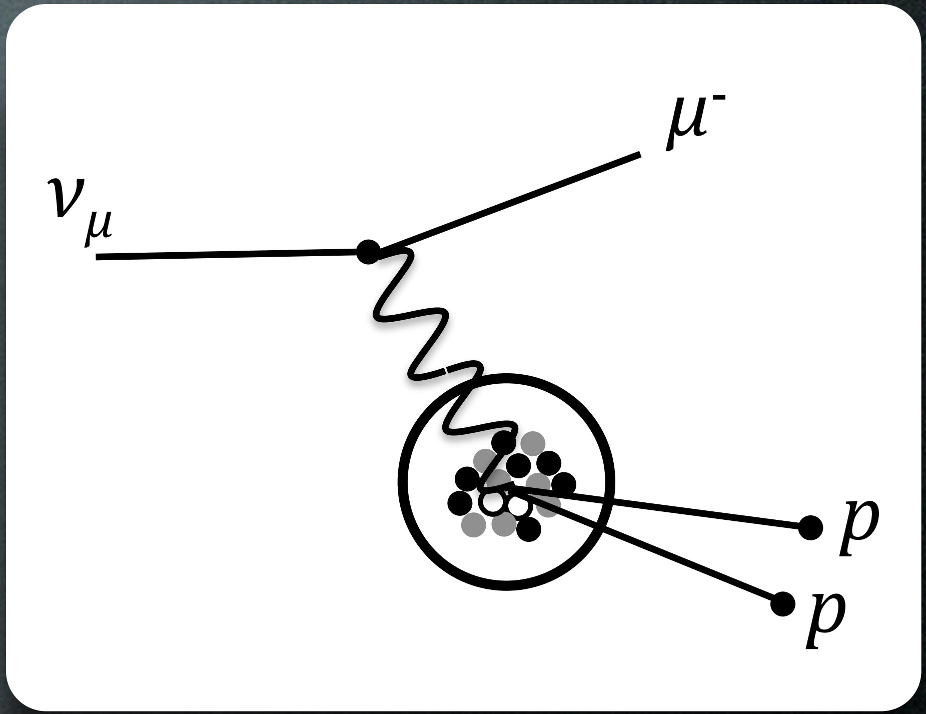
unchanged

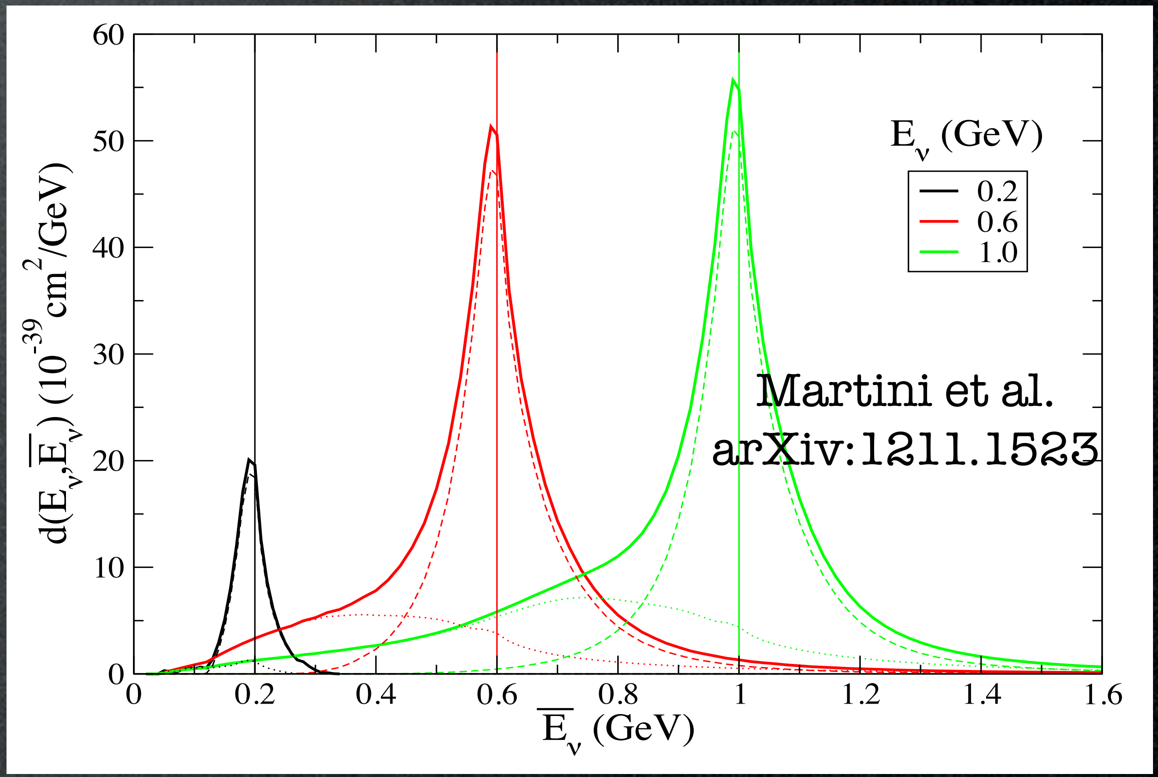
To be replaced by MEC

Any Other Systematic Limitations?

Multi-nucleon Events

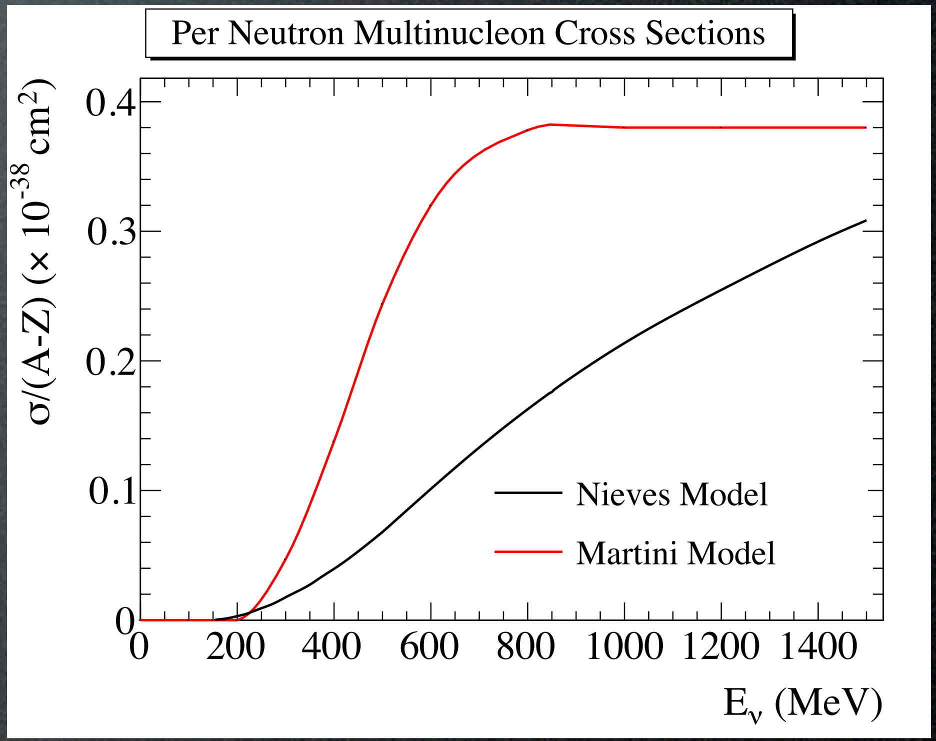
- Can experiments measure E_ν?
- Neutrino interaction models are now incorporating interactions with correlated nucleon pairs in the nucleus
    - This was not the case just a few years ago
    - If the current models are correct, a large fraction of events (~20-30%) can have a significant bias in reconstructed energy
- No direct data constraint exists
    - Oscillation experiments completely rely on models that were very different just 5 years ago

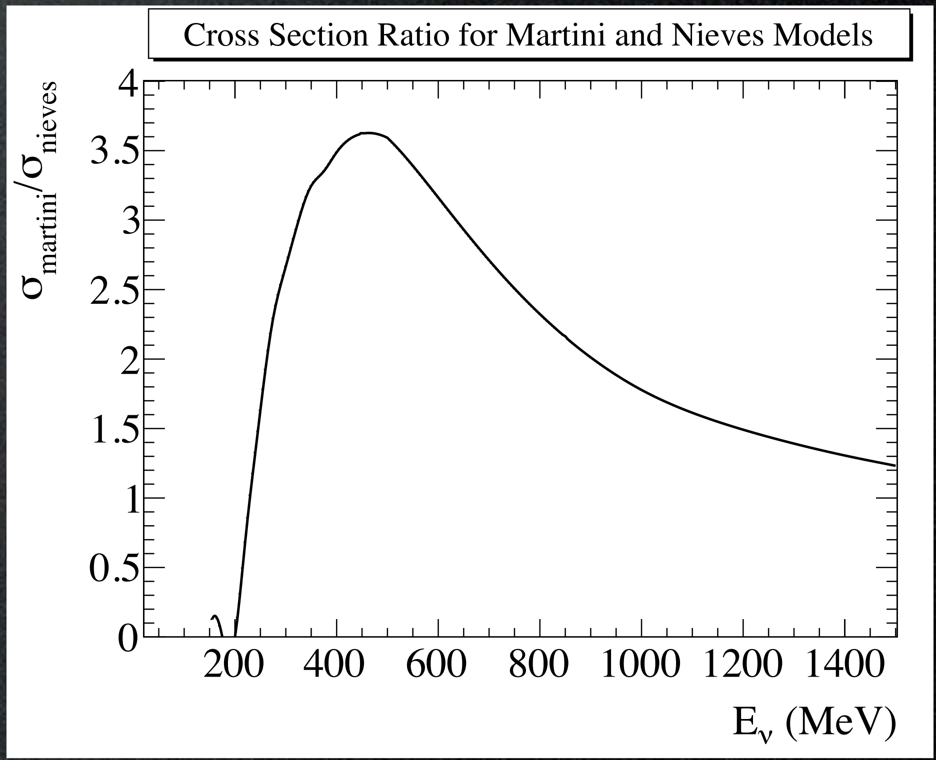




How Well are the New Models Understood?

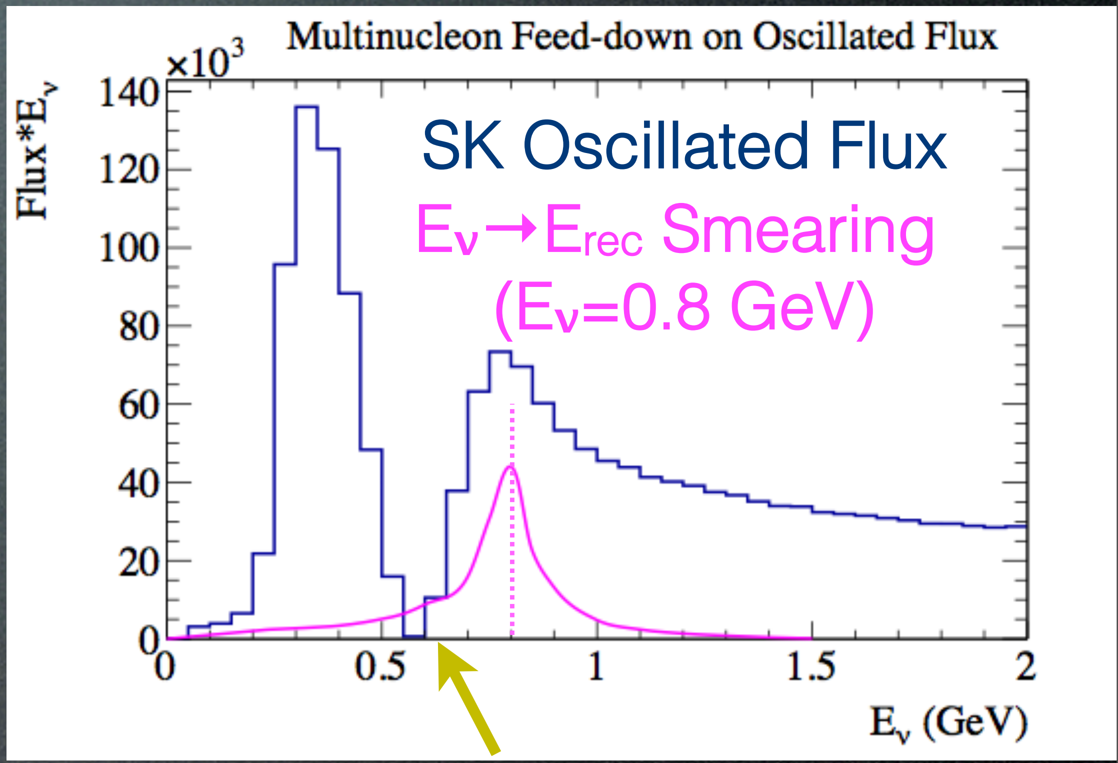
- It is very difficult to answer this question without a direct measurement
- However, the two most commonly used "new" models can be compared
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a factor of 2 to 3 over a large range of neutrino energies
- Which model is correct?
  - Is either model correct?
- How can we assign a systematic error to this process and trust that it is sufficient to cover the true model in nature?





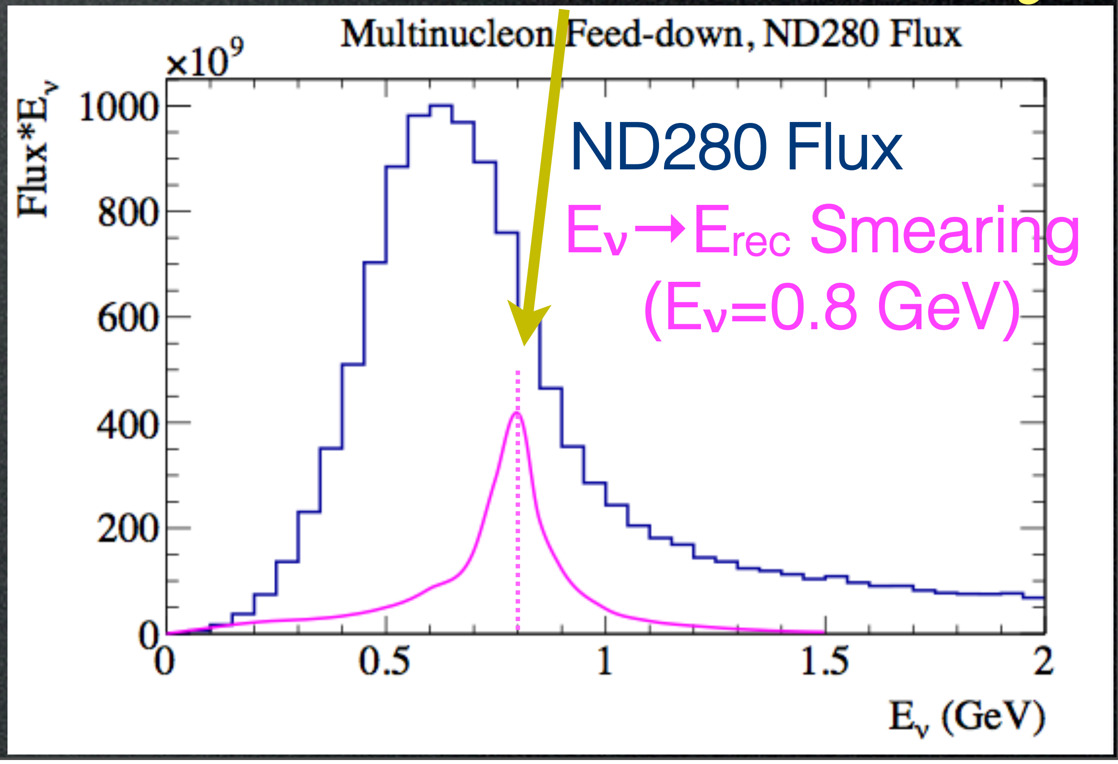
Isn't This is Why Oscillation Experiments Build Near Detectors?

- Shouldn't cross section systematics cancel in a near/far fit?
  - Some errors, like total normalization, will cancel
- However, multi-nucleon effect causes feed-down of events into oscillation dip
  - Cannot disentangle with near detectors
    - Energy spectrum is not oscillated
- More multi-nucleon = smaller dip
  - **Multi-nucleon effects are largely degenerate with mixing angle effect!**



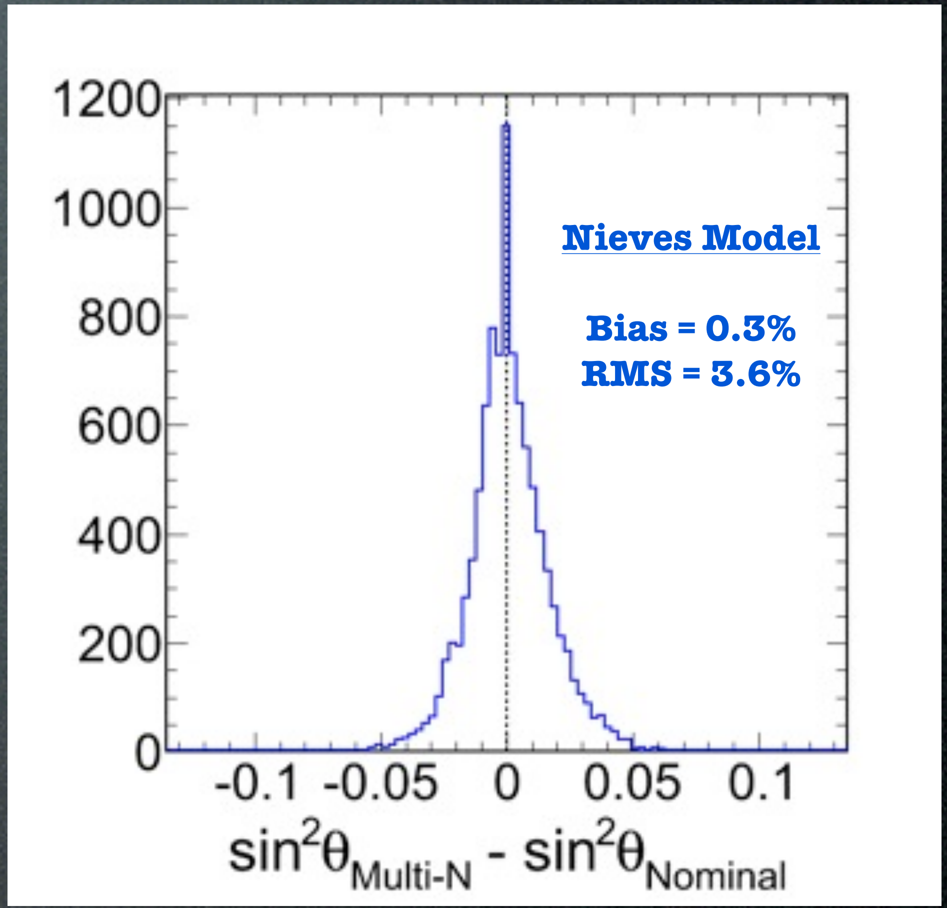
Mixing Angle Bias!

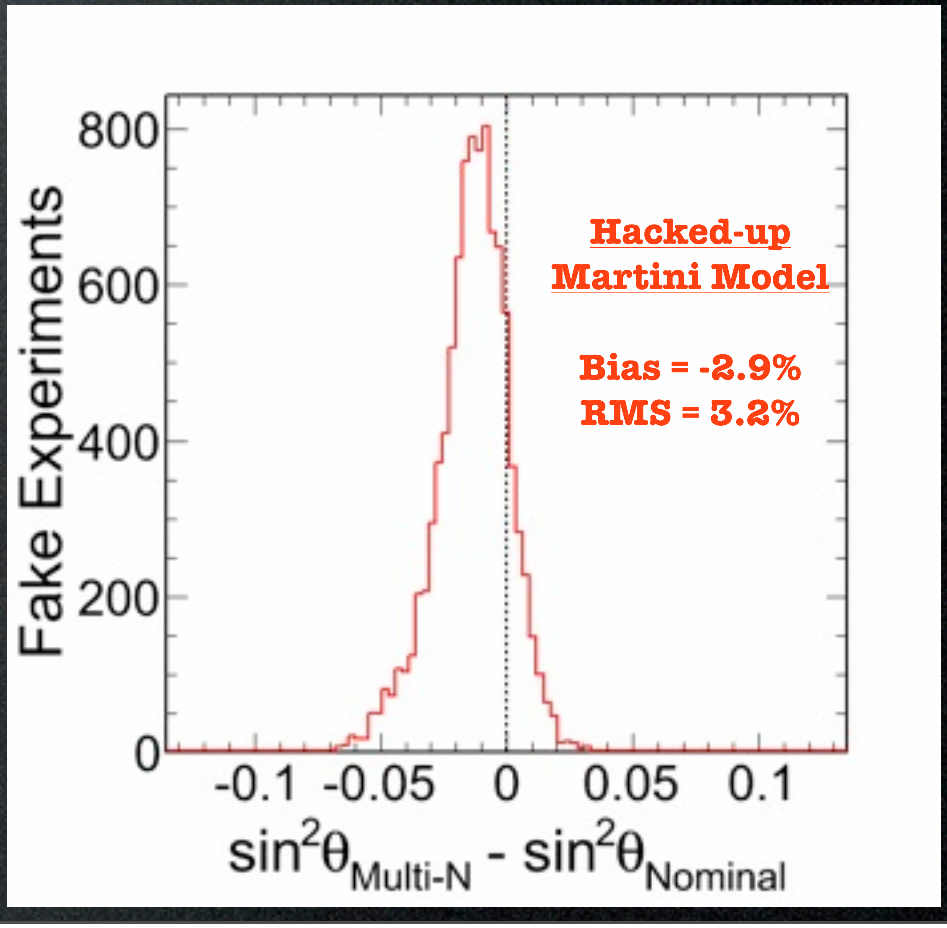
Near detectors lack sensitivity



Effect on T2K ν_μ Disappearance

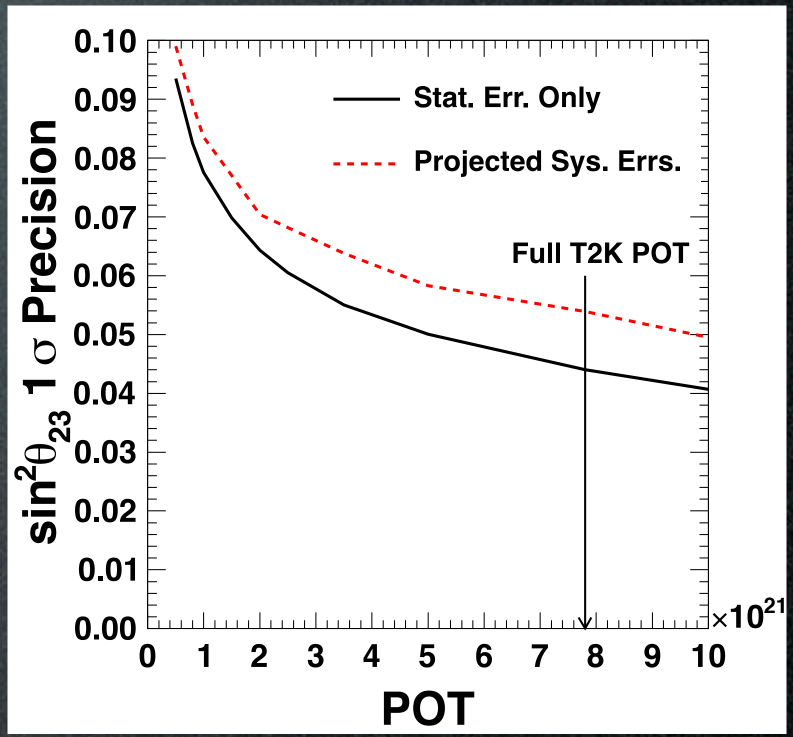
- Create “fake data” samples with and without multi-nucleon events
    - Compare fitted θ_{23}
- For Nieves model, “average bias” (RMS) = **3.6%**
- For Martini model, mean bias = -2.9%, RMS = 3.2%
    - Full systematic = $\sqrt{(2.9\%^2+3.2\%^2)}$ = **4.3%**
    - **This would be an important systematic error at full T2K POT**
        - Not yet incorporated into official results
- But this is just a comparison of 2 models
    - How much larger could the actual systematic uncertainty be?
- A new detector to experimentally address this currently in the proposal stage
    - See the **NuPRISM** talk later in this session

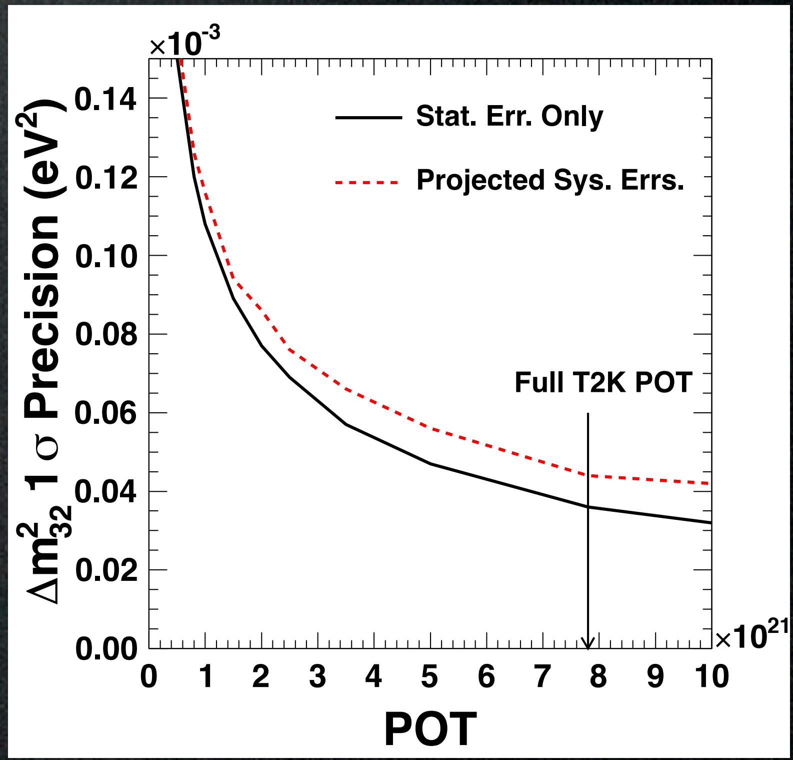




Summary

- T2K can make precise measurements of the ν_μ disappearance parameters
  - $\sin^2\theta_{23}$ 1σ uncertainty = 0.05-0.06
  - Δm^2_{32} 1σ uncertainty = 0.04-0.05 (10^{-3} eV^2)
- CP violation uncertainty for T2K only is limited to 2.5σ under current assumptions
  - However, some improvement in sensitivity may be possible by increasing ν_e statistics
    - Increase horn current from 250 kA to 320 kA (15%?)
    - Increase fiducial volume (20%?)
    - Include multi-ring event samples (50%?)
  - A 3σ T2K measurement may not be completely ruled out
- Combining with NOνA can significantly enhance CP sensitivity in the favorable regions of parameter space
- Ultimate sensitivity will depend on the ability to control systematic parameters (see NuPRISM talk)





Supplement

2015 Systematic Errors

- Further reduction of T2K systematic uncertainties has already been demonstrated by improving the cross section modeling

SOURCE	ν_e	ν_μ
φ+σ(ND-constrained)	26.0	21.8
w/ND280	3.1	2.7
φ+σ(ND-independent)	4.7	5.0
π secondary	2.4	3.0
SK DETECTOR	2.7	4.0
TOTAL without ND280	26.8	23.5
with ND280	**6.8**	**7.7**